# $D^*_{sJ}(2317)^+$ : a $P$ state from the light cone harmonic oscillator model?

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We show that the mass of the recently found meson, $D^*_{sJ}(2317)^+$ could be reproduced by an effective light cone Hamiltonian model with a harmonic oscillator potential as confinement — the light cone harmonic oscillator model.

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A recent experiment by the BABAR collaboration observes a new narrow $c\bar{s}$ state, $D^*_{sJ}(2317)^+$ with the invariant mass $M = 2.32$ GeV/$c^2$ [1]. The state has natural spin-parity and the low mass suggests a $J^\pi = 0^+$ assignment. In the convention of the quark model (QM), correspondingly, $L = 1$, $S = 1$ and $J = 0$, i.e., ${}^{2S+1}L_J = {}^3P_0$. However, as argued in Ref. [1], both the small mass and the small width are in conflict with most model predictions available then [2, 3, 4]. For example, the mass of this state is typically predicted between 2.4 and 2.6 GeV/$c^2$ in Refs. [2, 3, 4] (cf. Table I). Due to these conflictions, it is suggested in Ref. [1] either to modify those models or to attribute this state, e.g., as a four quark state. But we show here that $D^*_{sJ}(2317)^+$ is still consistent with the normal picture. The mass of $D^*_{sJ}(2317)^+$ could be reproduced by an effective light cone Hamiltonian model with a harmonic oscillator potential as confinement — the light cone harmonic oscillator (LCH) model without changing the parameters fixed previously.

The LCH model, a light-cone QCD-inspired model, with the mass squared operator consisting of a harmonic oscillator potential as confinement and a Dirac delta interaction, was proposed recently [5, 6]. This simple model presents an universal and satisfactory description of both singlet and triplet states of $S$-wave mesons and the corresponding radial excitations.

For the present purpose, the model Hamiltonian reads,

$$M^2_{\rm ho}\varphi(\vec{r}) = M^2\varphi(\vec{r}). \tag{1}$$

Compared to Refs. [5, 6], the Dirac-delta interaction is omitted here because it only acts on $S$ states. But we add a phenomenological spin-orbit term with the strength $\kappa$ being a free parameter to be determined by the data (For the results with a more reasonable spin-orbit term, see Ref. [7]). The mass squared operator is then

$$M^2_{\rm ho} = 2m_s\left(-\frac{\vec{\nabla}^2}{2m_r} + \frac{1}{2}m_s + v(r) + \kappa\vec{L}\cdot\vec{S}\right), \tag{2}$$

in units of $\hbar = c = 1$. $m_s$ and $m_r$ are the sum and the reduced mass of the two quarks with constituent quark masses $m_1$ and $m_2$. The masses for the strange and charm quarks were determined in Ref. [5, 6] as 0.478 and 1.749 GeV, respectively.

TABLE I: Masses of $c\bar{s}$ meson states with $L = 1$. The data for ${}^3P_2$ and ${}^1P_1$ are taken from Ref. [8]. Predictions from Ref. [3, 4] are also included for comparison. For the labels of each state, $n$ is the radial quantum number, $L$ the total orbital angular momentum, $S$ the total spin and $J$ the total angular momentum. $j$ is the total angular momentum of the strange quark which is conserved in the limit of large charm quark mass.

| $n^{2S+1}L_J$ | $n^jL_J$ | Data | Ref. [3] | Ref. [4] | This work |
|---|---|---|---|---|---|
| $0^3P_2$ | $0^{3/2}P_2$ | 2.573 | 2.59 | 2.581 | 2.573 |
| $0^1P_1$ | $0^{3/2}P_1$ | 2.536 | 2.55 | 2.535 | 2.494 |
| $0^3P_1$ | $0^{1/2}P_1$ | — | 2.55 | 2.605 | 2.412 |
| $0^3P_0$ | $0^{1/2}P_0$ | 2.32 | 2.48 | 2.487 | 2.328 |

The harmonic oscillator potential was introduced in Ref. [5, 6] as

$$v(r) = -c_0 + \frac{1}{2}c_2r^2, \tag{3}$$

where $c_0 = 0.807$ GeV and $c_2 = 0.0713$ GeV$^3$ are two universal parameters valid for all mesons. The mass squared was given analytically,

$$M^2_{nLJ} = 2m_s\left[N\sqrt{\frac{c_2}{m_r}} + \frac{1}{2}m_s - c_0 + E_{LS}\right], \tag{4}$$

where $N = (2n + L + 3/2)$ with $n = 0, 1, 2, \cdots$ the radial quantum number. The term of the spin-orbit splitting $E_{LS}$ is supposed to vanish for $S = 0$. For triplet states ($S = 1$),

$$E_{LS} = \begin{cases} +\kappa L, & \text{for } J = L + 1, \\ -\kappa, & \text{for } J = L, \\ -\kappa(L + 1), & \text{for } J = L - 1. \end{cases} \tag{5}$$

The mass of the singlet state $D_s({}^1P_1)$, which is independent of $\kappa$, is calculated from Eq. (4) as 2.494 GeV. It deviates from the experimental value $M(D_{s1}(2536)^+)$

= 2.536 GeV [8] by only ∼0.04 GeV. The agreement is reasonable considering that the mixing between the singlet and the triplet $J = 1$ states is not included in this simple model. For the same reason, we will use the theoretical mass of $D_s(^1P_1)$ and the data of $^3P_2$, $D^*_{sJ}(2573)^+$ to determine the parameter $\kappa$,

$$\kappa = \frac{1}{2m_s}\left[M^2(^3P_2) - M^2(^1P_1)\right] = 0.0899 \text{ GeV} , \quad (6)$$

where $m_s$ is the summation of the strange and charm quark masses. The masses of the other two triplet $P$ states, $^3P_1$ and $^3P_0$ are easily calculated from Eqs. (4) and (5) and given in Table I where predictions from Refs. [3, 4] are also included for comparison. The present prediction for the mass of the lowest $P$ state is very close to the data. This implies that $D^*_{sJ}(2317)^+$ might still be a "normal" meson consisting of two constituent quarks.

From the LCH model, the four $P$ states are equal-spacing in mass squared as seen from Eqs. (4) and (5) and Table I. Apparently this is not the case in the experiment. As mentioned before, one of the reasons might be that there is an admixture between $^1P_1$ and $^3P_1$ because only the total angular momentum $\vec{J} = \vec{L} + \vec{S}$ should be conserved. This coupling is not included in the simple LCH model.

There are many other phenomenological scenarios for the spin-orbit splitting in hadron spectroscopy, see e.g. Ref. [9]. Inclusion of those scenarios would improve the prediction power of our model but would also bring out more complication. We therefore leave that for a future task.

In summary, the $P$ states of the charmed strange meson are investigated by using an effective light cone Hamiltonian model with a harmonic oscillator potential. We conclude that $D^*_{sJ}(2317)^+$ can still be consistent with the normal picture of mesons. The investigation of other $L \neq 0$ states in all $q\bar{q}$ sectors is in progress.

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